

Further evidence for a time-dependent initial mass function in massive early-type galaxies

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ABSTRACT

Spectroscopic analyses of gravity-sensitive line strengths give growing evidence towards an excess of low-mass stars in massive early-type galaxies (ETGs). Such a scenario requires a bottom-heavy initial mass function (IMF). However, strong constraints can be imposed if we take into account galactic chemical enrichment. We extend the analysis of Weidner et al. and consider the functional form of bottom-heavy IMFs used in recent works, where the high-mass end slope is kept fixed to the Salpeter value, and a free parameter is introduced to describe the slope at stellar masses below some pivot mass scale ($M < M_P = 0.5M_\odot$). We find that no such time-independent parameterisation is capable to reproduce the full set of constraints in the stellar populations of massive ETGs – resting on the assumption that the analysis of gravity-sensitive line strengths leads to a mass fraction at birth in stars with mass $M < 0.5M_\odot$ above 60%. Most notably, the large amount of metal-poor gas locked in low-mass stars during the early, strong phases of star formation results in average stellar metallicities $[M/H] \lesssim -0.6$, well below the solar value. The conclusions are unchanged if either the low-mass end cutoff, or the pivot mass are left as free parameters, strengthening the case for a time-dependent IMF.

Key words: galaxies: evolution – galaxies: star formation – galaxies: stellar content – stars: luminosity function, mass function

1 INTRODUCTION

The distribution of stellar masses in galaxies, i.e. the stellar initial mass function (IMF), is of fundamental importance for describing stellar populations. Amongst other things, the IMF drives the chemical evolution of galaxies and defines the stellar mass-to-light ratios (M_\star/L). The IMF has been intensely studied in the Milky Way (MW) and nearby dwarf galaxies, and it has been found mostly invariant for a large range of physical parameters (Kroupa 2002; Chabrier 2003; Kroupa et al. 2013).

However, in recent years this universality of the IMF has been called into question by a number of new observational results (see, e.g. Cenarro et al. 2003; Hoversten & Glazebrook 2008; Meurer et al. 2009; Gunawardhana et al. 2011; van Dokkum & Conroy 2010, 2012; Cappellari et al. 2012; Ferreras et al. 2013; Weidner et al. 2013). On a first glance, not all of these

results agree well with each other. While, for example, Gunawardhana et al. (2011) find that the IMF becomes increasingly top-heavy in galaxies with a high star formation rate, other studies suggest bottom-heavy IMFs for massive early galaxies (ETGs), systems which are believed to have formed in a massive starburst. More hints about top-heavy IMFs have also been found in the bulges of M31 and the MW (Ballero et al. 2007) as well as in massive globular clusters and ultracompact dwarf galaxies (Dabringhausen et al. 2012; Marks et al. 2012).

The rise of large and deep galaxy surveys in recent years opened a new angle on stellar populations in galaxies. For example, Cappellari et al. (2012) used integral field spectroscopy and photometry of a volume-limited catalogue of 260 ETGs to constrain the populations in these galaxies. They found that, independent of the choice of dark matter halo model for the galaxies, the SDSS r -band M/L ratios suggest a systematic transition from a standard IMF (e.g. Kroupa 2001) towards a distribution with heavier stellar M/L in the more massive galaxies (by $\sim 60\%$ at

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$\sigma \sim 300 \text{ km s}^{-1}$). Bottom-heavy IMFs for ETGs had already been suggested by studies of abundance line indicators in ETGs (Cenarro et al. 2003) and bulges of late-type galaxies (Falcón-Barroso et al. 2003). The need for non-standard IMFs had also been shown from abundance ratios and the colours of ETGs (Vazdekis et al. 1996, 1997). More recently, van Dokkum & Conroy (2010, 2012) analysed the gravity-sensitive indices Na8190 and FeH0.99 and found strong evidence for a bottom-heavy IMF in ETGs.

This view is however not without challenge. Smith & Lucey (2013) showed a strong lens massive ETG and compared the stellar lensing mass with mass estimates from population synthesis modelling. They found no striking deviation from a standard IMF. This galaxy is, however, very extended whereas compactness has been suggested (Läsker et al. 2013) as a driver for the IMF changes.

Galactic chemical enrichment provides an additional constraint on the IMF, as the distribution of stellar masses plays an essential role in the enrichment of stellar populations. In Weidner et al. (2013) it was shown that a time-independent standard bimodal IMF – with a power-law at the high mass end, and a smooth tapering at low masses, as defined in Vazdekis et al. (1996) – was not capable of explaining all the observables of massive ETGs. The assumption of a bottom-heavy IMF results in low overall metallicities for the stellar populations, in contradiction with the observations. The solution, first proposed in Vazdekis et al. (1996, 1997), and revisited in Weidner et al. (2013) involves a time-dependent IMF, where a top-heavy phase, expected during the first stages of evolution, is followed by a bottom-heavy phase. This scenario is physically motivated by the fact that the strong starbursts expected in massive galaxies at high redshift inject vast amounts of energy into the ISM, changing the physical conditions to a highly turbulent medium at high pressure, perhaps inducing a strong fragmentation process (Hopkins 2013; Chabrier et al. 2014). However, there is an additional aspect not covered in Weidner et al. (2013): the chosen bimodal IMF tightly links, by construction, the high-mass end to the low-mass end, so one could still envision a distribution where the high-mass end is kept at a Salpeter-like value (Salpeter 1955), whereas the slope at the low-mass end is left as a free parameter. Such a functional form of the IMF is adopted by some of the groups in this field (see, e.g. Conroy & van Dokkum 2012). In this letter, we explore the consequences of this approach from the point of view of galactic chemical enrichment, and we find a significant mismatch to explain simultaneously the age-, metallicity- and gravity-sensitive features of massive galaxies. Therefore, the need for a time-dependent IMF is more compelling.

This letter is structured as follows: §2 provides a generic working definition for the functional form of the IMF. In §3 the chemical evolution model with the variable IMF used here is described. The results from our model calculations are presented and discussed in §4. Finally, §5 summarizes the conclusions. For reference, Tab. 1 shows conservative constraints from the literature on the observables used to test the hypothesis of a time-independent IMF.

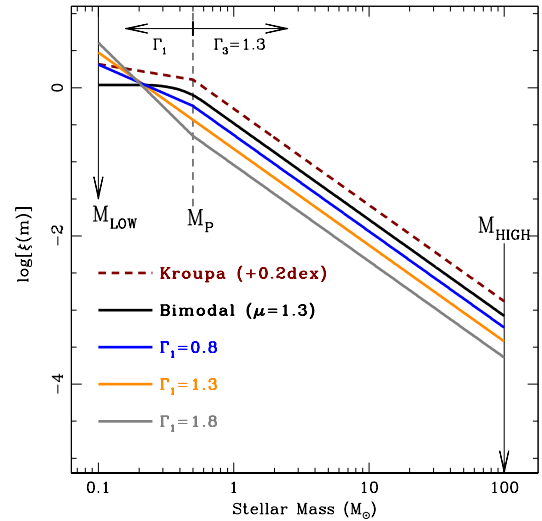


Figure 1. Functional form of the Initial Mass Function adopted here, along with standard choices from the literature (see text, and equation 1 for details).

2 A FUNCTIONAL FORM OF THE IMF

We assume a simple description for the initial mass function, as a truncated power law, namely¹ (see Fig. 1):

$$\xi(m) \equiv \frac{dN}{dm} = \begin{cases} N_1 m^{-(1+\Gamma_1)}, & M_{\text{LOW}} < m \leq M_P \\ N_3 m^{-(1+\Gamma_3)}, & M_P < m < M_{\text{HIGH}}, \end{cases} \quad (1)$$

where the slopes are given with respect to log-mass units. We assume the high-mass end branch to have a Salpeter-like slope, i.e. $\Gamma_3 = 1.3$. Our fiducial case fixes the mass scale of the pivot point at $M_P = 0.5 M_\odot$; and the mass range: $M_{\text{LOW}} = 0.1 M_\odot$; $M_{\text{HIGH}} = 100 M_\odot$. Note that the case $\Gamma_1 = 1.3$ is similar to a Salpeter (1955) IMF. Variations of this expression have been used in the literature to describe the IMF (see, e.g., Miller & Scalo 1979; Kroupa 2001; Marks et al. 2012) and have been used to explain the signature of low-mass stars in the spectra of ellipticals (e.g. Conroy & van Dokkum 2012) as well as analyses of the underlying chemical enrichment associated to these systems (Vazdekis et al. 1996, 1997; Bekki 2013). Spectroscopic data from gravity-sensitive features can only constrain the mass fraction in low-mass stars at birth (see Fig. 21 of La Barbera et al. 2013), leaving a significant uncertainty with respect to the stellar mass-to-light ratio (Ferreras et al. 2013), and complicating comparisons with dynamically-based studies (e.g. Cappellari et al. 2012; Smith 2014). The assumption of a functional form of the IMF is needed for an adequate comparison.

In La Barbera et al. (2013) it was found that regardless of the choice of IMF, the gravity-sensitive spectral features imply a conservative constraint on the stellar mass fraction, at birth, in stars with $M < 0.5 M_\odot$ ($F_{0.5}$). Massive ETGs are

¹ Note we use the 1,3 subindex notation as in, e.g. Kroupa et al. (2013). The missing subindex 2 would refer to an intermediate mass region that we do not consider here.

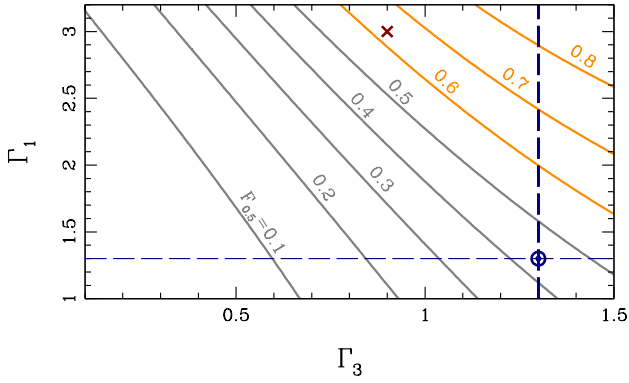


Figure 2. Contours of $F_{0.5}$ as a function of the two IMF slopes, Γ_1 and Γ_3 (see text for details). The thick vertical dashed line represents the fiducial set of models explored in this letter, along with a top- + bottom-heavy model (cross, see §3). The circle corresponds to a standard Salpeter-like IMF. Values $F_{0.5} \gtrsim 0.6$ are expected for massive ETGs (orange contours).

found to have $F_{0.5} \gtrsim 0.6$. With the assumptions adopted here, no model with $\Gamma_1 < 1.5$ is capable of explaining the IMF-sensitive spectral features of massive ETGs (see Fig. 2).

3 CHEMICAL ENRICHMENT MODELLING AND OBSERVATIONAL CONSTRAINTS

We explore a set of phenomenological models tracking galactic chemical enrichment through a reduced set of parameters. These models are presented in detail in Ferreras & Silk (2000a,b). In Weidner et al. (2013) we apply them to a time-dependent IMF in order to explain the gravity-sensitive line strengths found in massive ETGs. In a nutshell, the buildup of the stellar component of a galaxy is described by four parameters: a gas infall timescale (τ_f), a star formation efficiency (C_{eff}), that follows a Schmidt law, a formation redshift (z_{FOR}) at which the whole process starts, and a fraction of gas ejected in outflows (B_{out}).

We ran a grid of models adjusted to the stellar populations in massive ETGs (see, e.g. de La Rosa et al. 2011). In order to achieve a homogeneously old population, we need to assume an early start for the star formation process ($z_{\text{FOR}} = 3$), and negligible outflows ($B_{\text{out}} = 0$). Changes in these two parameters will mostly induce an overall shift in the average age and metallicity, respectively. Furthermore, non-negligible outflows would produce lower metallicities, hence strengthening our conclusion towards a time-dependent IMF (see §4). The other two parameters, namely the gas infall timescale (τ_f) and star formation efficiency (C_{eff}) are left as free parameters in the grid. The model grids are run for a range of IMF slopes, $1 < \Gamma_1 < 2.5$.

Fig. 3 shows the results of the chemical enrichment modelling for three choices of IMF slope: Salpeter ($\Gamma_1 = \Gamma_3 = 1.3$, left); bottom-heavy ($\Gamma_1 = 2.2$, $\Gamma_3 = 1.3$, middle), and the additional case of a top + bottom heavy IMF ($\Gamma_1 = 3$, $\Gamma_3 = 0.9$, right). For the latter, we modify the high-mass slope, Γ_3 , to values that would be compatible with the observations of top-heavy IMFs in star-forming systems (e.g. Gunawardhana et al. 2011), changing in ad-

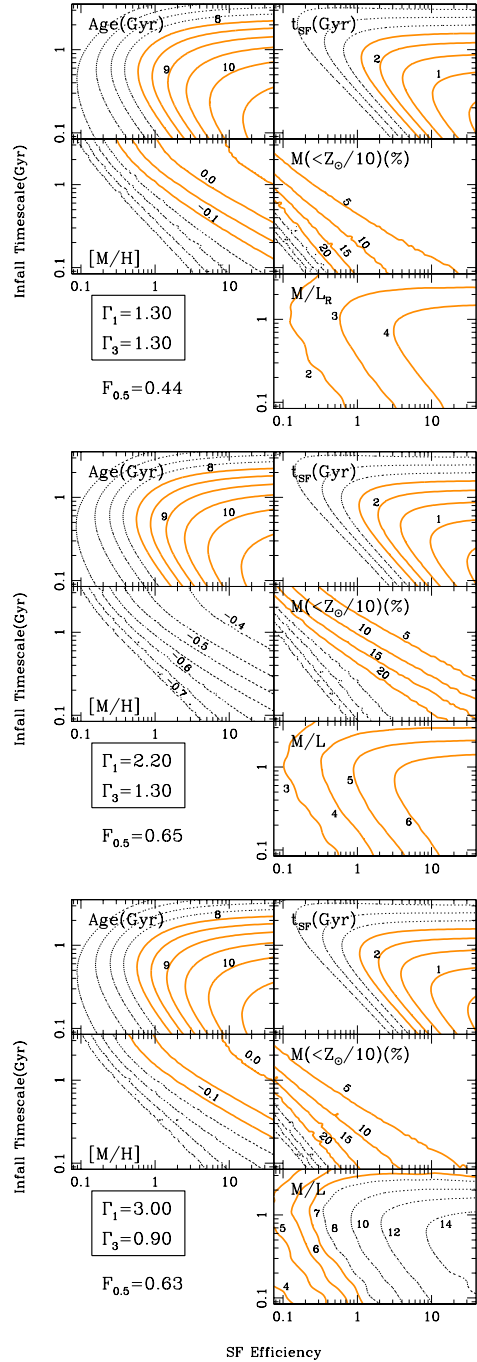


Figure 3. Contour plots with the main observable constraints from the chemical enrichment code corresponding to a massive early-type galaxy (i.e. with a stellar mass $\gtrsim 10^{11} M_{\odot}$). Three different choices of IMF slope are considered, a Salpeter-like case (top), a bottom-heavy case (middle), and a top + bottom-heavy case (bottom). The contours that are compatible with the observational constraints (Tab. 1) are shown as thick orange lines, the remainder as dotted contours. The contours in age and τ_{sf} are spaced in intervals of 0.5 Gyr. The contour intervals for $[M/H]$ and $M(< Z_{\odot}/10)$ are 0.05 dex and 5%, respectively. All the contours in M/L are labelled, and measured with respect to the SDSS-r band. See text, and Tab. 1 for details.

Observable	Constraint	Reference
Age (Gyr)	[8, 10]	(1)
[M/H]	[−0.1, +0.2]	(1)
t_{SF} (Gyr)	[0.5, 2.0]	(2)
$M_s(< Z_{\odot}/10)$	[0.05, 0.20]	(3)
$F_{0.5}$	[0.6, 0.8]	(4)
$\Upsilon_r/\Upsilon_{r,\odot}$	< 7.0	(4)

Table 1. Constraints on the general properties of the unresolved stellar populations in massive early-type galaxies. The uncertainties are rough estimates, quoted at a conservative 1σ level. The references are: (1) Trager et al. (2000); Thomas et al. (2005); (2) de La Rosa et al. (2011); (3) Vazdekis et al. (1997); (4) La Barbera et al. (2013)

dition the low-mass slope, Γ_1 , to accommodate the high values of $F_{0.5}$. For each case, we show (counter-clockwise from the bottom-right) contours of stellar mass-to-light ratio (in the SDSS- r band); mass fraction in low-metallicity stars ($M(< Z_{\odot}/10)$); star formation lapse (t_{SF}); average age, and average metallicity ([M/H]). Averages are mass-weighted. The star formation lapse is defined as the time period between the 25th and 75th percentiles of the stellar mass build-up in the galaxy. t_{SF} is therefore tightly linked to [Mg/Fe]. As a very conservative estimate, we assume that values $t_{\text{SF}} \gtrsim 2$ Gyr are in conflict with the observed overabundance of [Mg/Fe] in massive ETGs (de La Rosa et al. 2011). $M(< Z_{\odot}/10)$ is defined as the fraction of stellar mass with metallicity below 1/10 of solar. This is an indicator of the G-dwarf problem (Pagel & Patchett 1975). It is a well-known fact that some models can produce old, and overall metal-rich populations, although with a significant tail of low-metallicity stars. Models with a mass fraction over 10–20% in low-metallicity stars would be in conflict with the observations of massive ETGs (Vazdekis et al. 1996, 1997; Maraston & Thomas 2000; Nolan et al. 2007).

4 RESULTS & DISCUSSION

Fig. 3 shows that the Salpeter model (*left*) is capable of recreating the old, metal rich, [Mg/Fe] over-abundant populations without a significant low-metallicity trail. However, the fraction in low-mass stars ($F_{0.5} = 0.44$) is in conflict with the recent interpretation of gravity-sensitive spectral features (La Barbera et al. 2013). The top- + bottom-heavy model (*right*) is challenged by the overly high values of M/L in the region of parameter space compatible with the age/metallicity constraints. The same result would hold if we chose to keep Γ_3 as a free parameter. Therefore, we rule out the option of a change in both slopes, and hereafter focus on the case where the high-mass end slope is fixed to the Salpeter-like value ($\Gamma_3 = 1.3$). The bottom-heavy model (*middle*) allows for a higher low-mass fraction ($F_{0.5} = 0.65$) at the price of locking too much gas in low-mass stars during the early (metal-poor) stages. The average metallicities are significantly lower than those derived from the observations in massive ETGs.

One could consider additional changes of the functional form of the IMF, most notably changing either the pivot point (M_P) – motivated by a change in the physical properties of the star forming regions (see, e.g. Larson 2005) –

or the low-mass end (M_{LOW}) – as suggested in the recent analysis of ETG lenses (Barnabè et al. 2007). Note that we emphasize in this letter that all these changes would relate to an otherwise *time-independent* IMF. However, from the previous figure, it is expected that such changes nevertheless lock large masses of low-metallicity stars, leading to results that are incompatible with the metal-rich populations found in massive galaxies. To further illustrate this point, we show in Fig 4 a χ^2 estimator based on the observational constraints presented above (see Tab. 1), where Gaussian constraints are imposed at the 1σ level over the allowed intervals, in effect producing very conservative limits. For M/L – where the constraint derives from *dynamical* M/L measurements – we simply penalize the likelihood for values higher than $\Upsilon_r = 7\Upsilon_{r,\odot}$ using a Gaussian with $\sigma = 0.5$. We consider several cases, where either a range for the low-mass end (M_{LOW} , top panel) or the pivot mass (M_P , bottom panel) are explored in a time-independent IMF. The solid lines correspond to different cases where all four constraints are imposed. The dashed lines show, for comparison, the case where the $F_{0.5}$ constraint is removed from the analysis. As reference, the horizontal dotted line in both panels represent the fiducial, time-dependent model² A of Weidner et al. (2013), where a top-heavy IMF is followed by a sharp transition towards a bottom-heavy IMF after 0.3 Gyr. Note the different behaviour with respect to changes of either the low-mass end of the IMF, or the pivot mass scale. In the top panel, a transition is apparent at $M_{\text{LOW}} = 0.10M_{\odot}$, above which very bottom-heavy IMFs seem to be favoured, with the best case at $0.15M_{\odot}$. Nevertheless, even this option is rejected with respect to a time-dependent scenario.

Fig. 4 confirms that for a wide range of options, a time-independent IMF is incompatible with constraints from galactic chemical enrichment. Although the proposal presented in Weidner et al. (2013) is a simple toy model, this letter supports the need for a time-dependent mechanism that tips an initial top-heavy IMF in a strongly star-forming system, towards a bottom-heavy IMF during the final stages of the starburst. Such a mechanism would reconcile the apparent contradiction between the observations of star-bursting systems and the properties of quiescent galaxies that underwent a star-bursting phase in the past. We emphasize that the relatively long duration ($\sim 1 - 2$ Gyr) of a strong star formation phase in massive ETGs at high redshift is expected to cause this transition.

5 CONCLUSIONS

We explore a model of galactic chemical enrichment, with the assumption of a time-independent IMF, with several free parameters controlling the contribution of low- and high-mass stars. The functional form (presented in §2) is representative of the typical functions explored in the literature. A comparison of our models with conservative observational constraints in massive ETGs (Tab. 1) reject this hypothesis, mainly based on the locking of too many low-mass metal-poor stars during the first phases of formation, and on the

² We emphasize that the functional form of the (bimodal) IMF in Weidner et al. (2013) changes both low- and high-mass ends with a single parameter, Γ .

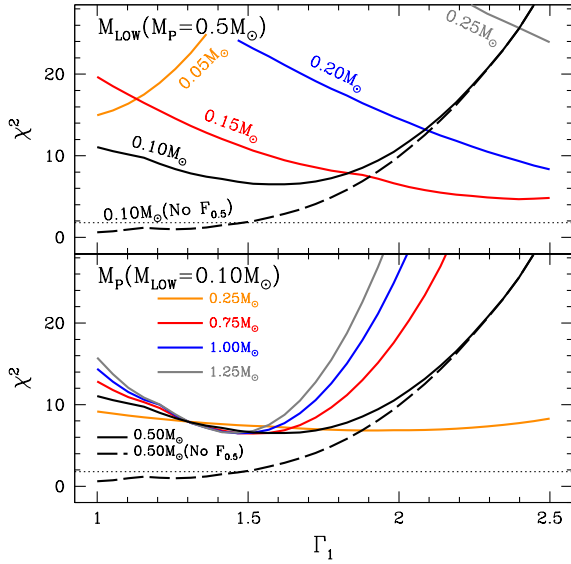


Figure 4. Fits to the extended models, where the low-mass end of the IMF (top), or the pivot mass (bottom) are considered as free parameters in a time-invariant IMF. The χ^2 values are shown for several cases (solid lines). We illustrate the constraining power of $F_{0.5}$ by including the case where this constraint is removed from the analysis (dashed lines). For reference, the χ^2 of a time-dependent IMF (model A in Weidner et al. 2013) is shown as a dotted horizontal line in both panels (where all constraints from Tab. 1, including $F_{0.5}$, are imposed).

assumption that the recent observations of gravity-sensitive line strengths result in a constraint on the mass fraction in low-mass stars at birth ($F_{0.5} > 0.6$). The best-fit time-independent models give stellar metallicities $[M/H] \sim -0.6$, i.e. significantly lower than the observational constraints – although higher than the metallicities expected for a time-independent “bimodal” IMF as defined in Vazdekis et al. (1996). In contrast, a simple time-dependent model, justified by the large energy injection during the strong star bursting phase in massive galaxies, leads to a consistent picture with an overall old, metal-rich and bottom-heavy stellar population, as suggested by Vazdekis et al. (1996, 1997) and, more recently by Weidner et al. (2013).

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